Recent developments in GENIE

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Neutrinos from Accelerators (NuFact2023)
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for the GENIE Collaboration

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Genie

UNIVERSAL NEUTRINO GENERATOR
& GLOBAL FIT

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GENIE Collaboration and Mission

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Core mission (details in here)

- **Modern event generation platform** for the neutrino community
- **State-of-the-art, universal comprehensive models** of neutrino interactions, **from MeV to PeV energy scales**
- Complementary electron, hadron, BSM event generators
- **Estimates of modelling uncertainties** from a **global analysis of scattering data** (neutrino, electron, hadron probes)

GENIE plays a unique and useful role

> *'All models are wrong,* **but some are useful***'*
>
> — George Box, British statistician (1976)

- Provides **large constellation of alternative models and tunes**
  - Helps interpreting data and diagnosing data/MC discrepancies
- Has **community-supported experimental interfaces and tools**
  - Integrated in the MC chain of all neutrino experiments, from low energy reactor expts to high energy CERN FPF expts and neutrino telescopes!
- **De-facto common platform** for model implementation.
- Provides **community coordination and support**
  - **GENIE Incubator** guides/supports large number of community developers
    - GENIE plays a crucial role reviewing, validating, improving, integrating community contributions
  - Regular **User Forum**; Established **experiment liaisons**
- Very **broad focus** and an emphasis on universal models.

Brief release history

http://releases.genie-mc.org

GENIE v2.* (Auk series):

- 2007-2018; 27 releases (last release, v2.12.10, published on Feb 2018)
- **Strong emphasis on tools** and interfaces; Quick experiment adoption
- **Well understood empirical model** a "standard candle" for the analysis and interpretation of neutrino data, but severely outdated now

GENIE v3.* (Bear series):

- 2019-present; 7 releases (latest release, v3.4.0, published on Mar 2023)
- New technical capabilities (eg. tune support, continuous integration)
- Improved physics modelling / **large constellation of alternative models**
- **Multiple comprehensive model configurations and tunes**
- **Powerful associated global analysis**
- Progress towards **complete uncertainty evaluation** of its main models

GENIE v4.* (Cheetah series):

- TBD; Likely in 2025
- In support of main experimental results in 2025-30 (JUNO, SBN, other)
- Key modelling and tuning upgrades

Summary of main new developments since v3 - I

completed (released) - completed (appears in next release) - in progress - planning

Physics modelling:

- New **1p1h/2p2h** models:
  SuSAv2, CRPA, QMC STA [10] *[Josh Barrow et al.]*, SF *[Noah Steinberger et al.]*
- New **pion production** models:
  MK, DCC [53, 54] *[Igor Kakorin et al.]*
- **Hadronization** modelling:
  PYTHIA8 in AGKY, LEPTO interface to PYTHIA,
  Complete migration to PYTHIA8 *[Robert Hatcher et al.]*,
  In-medium effects to hadronization [5] *[CA]*
- New **FSI** models:
  Interfaces to G4 Bertini and Liége (INCL) cascades.
- New **nuclear de-excitation** models:
  Modules based on TALYS [24] *[Jie Cheng et al.]*

Summary of main new developments since v3 - II

- New **nuclear initial state** modelling:
  Correlated Fermi Gas
- Adding **missing processes**:
  Coherent NC 1γ production (Δ contribution, complete model *[Marco Roda et al.]*)
- **High energy** neutrino interactions:
  NLO DIS cross-section model and event generation modules,
  Combining low-Q^2 data with pQCD using ML [23] *[Alfonso Garcia et al.]*
- **Low energy** neutrino interactions:
  CEvNS cross-section model and event generation modules
- **Electron** scattering:
  Bosted-Christy fit of eA scattering data,
  MAID E/M form factors [59] *[Julia Tena Vidal et al.]*
- New or upgraded **BSM** models:
  Boosted Dark Matter, Dark Neutrino, and Heavy Neutral Lepton (HNL) generators
  HNL extensions: Detailed treatment of polarization; Heavier HNL production and decay (enable searches above K mass, and w/ τ mixing); Extension of Lagrangian model machinery to incorporate user input *[Komninos-John Plows et al.]*

Summary of main new developments since v3 - III

Tuning:

- New tune of non-resonance bkg using H/D data
- New neutrino-induced hadronization tune
- New nuclear CC0π tune
- New global tune of TKI observables *[Weijun Li et al.]*
- FSI tuning and common uncertainty parameterization for all GENIE FSI codes

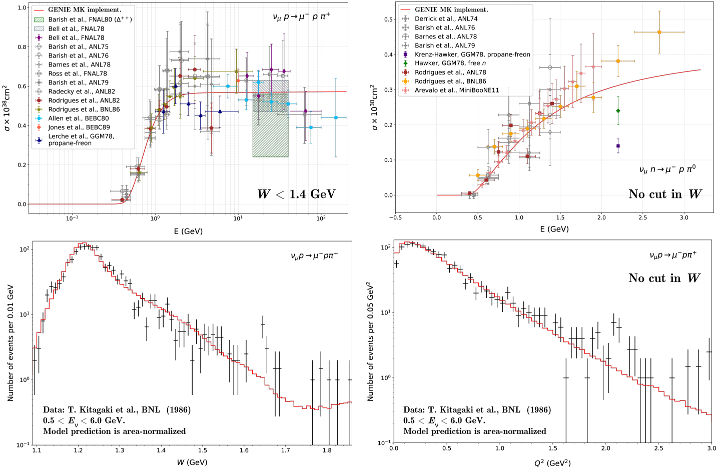
Tools and experimental interfaces:

- Event Library generator interface, enabling reuse of extended GENIE flux and geometry drivers by external generators.
- New toolkit for calculations based on tabulated hadron tensors.
- Complete support of GENIE tunes in ReWeight *[Qiyu Yan et al.]*

Impossible to summarize this body of work in 15'.
Only a birds-eye view and **very select highlights** in this talk.
More info: See the back up slides, referenced papers and other recent talks.

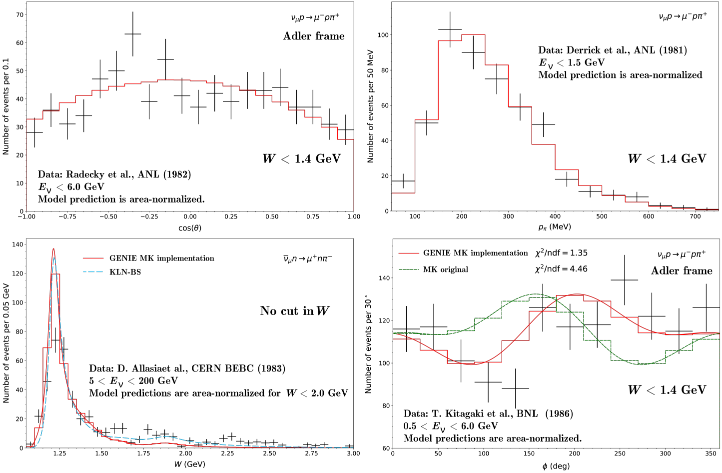
New cross-section modelling highlights - I

Complete implementation of the MK model [44, 45] by the Dubna group ($\geq$ v3.6.0).



New cross-section modelling highlights - II

Complete implementation of the MK model [44, 45] by the Dubna group ($\geq$ v3.6.0).



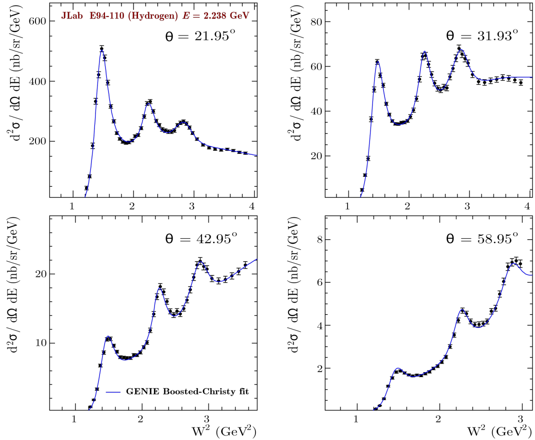
New cross-section modelling highlights - III

Addition of Bosted-Christy fit [21, 25] of electron data by the Dubna group ($\geq$ v3.4.0).

Data in the Bosted-Christy fit:

Data Set	Q^2_{Min} (GeV^2)	Q^2_{Max} (GeV^2)	# Data Points
E94-110 [5]	0.18	5	1259
E00-116 [14]	3.6	7.5	256
E00-002 [15]	0.06	2.1	1346
SLAC DIS [16]	0.6	9.5	296
Photoproduction (Old) [17–19]	0	0	242
Photoproduction (DAPHNE) [20]	0	0	57

- The model is presented as 2-fold cross section with valid kinematic range: $0 < Q^2 < 10$ GeV^2 and $0 < W < 3$ GeV.
- The model is inclusive. Currently not coupled to event generation.



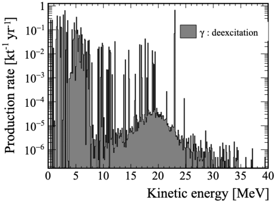
Nuclear environment post hard scattering

An important feature of GENIE v3 is the availability of **4 interchangeable and independently-developed FSI codes**:

- INTRANUKE/hA, an *effective* model with limited applicability
- INTRANUKE/hN, a full home-grown INC model
- G4 Bertini cascade [41]
- Liége (INCL) cascade [22, 29, 30]

This allows a careful exploration of FSI effects and their systematics.

- This is complemented by important work led by JUNO (Jie Cheng et al.) [24] to develop GENIE nuclear de-excitation modules using the **TALYS library**.
- Currently, we're working with the authors of the TALYS modules to determine how to best integrate in GENIE, and eliminate double counting when coupled to FSI modules with own de-excitation routines.



Reproduced from [24].

Interface to the G4 Bertini cascade ($\geq$ v3.2.0)

- G4 work [41] re-engineering the INUCL code [60].
- Model simulates the fast (10^{-23} - 10^{-22} s) phase of particle collisions by solving the Boltzmann equation on the average.
- Based on the INC model of Alsmiller, Bertini, Guthrie [40] [14] [15].
- Pre-equilibrium emission is based on the Griffin exciton model [39].
  - the excited state of the nucleus is characterised by the number of particles and holes created.
- For the simulation of the slower (10^{-18} - 10^{-16} s) compound phase, **several competing evaporation / break up models** are used.
  - **Nuclear explosion**; Allowed in extreme cases (for light nuclei and excitation energies much larger than the binding energy).
  - **Fission**; Based on the model of Bohr and Wheeler [19]
  - **Evaporation of nucleons & light fragments**; Based on the Weisskopf theory of particle emission [62] [63] or, for lighter nuclei ($A < 28$), on the Generalised Evaporation Model [47].
  - **Evaporation of photons**, with discrete and continuous (from giant resonance de-excitation) energy levels; Modelled using tabulated transition probabilities

Genie

Interface to the Liége (INCL) cascade ($\geq$ v3.2.0)

INCL is an advanced intranuclear cascade code [22, 29, 30].

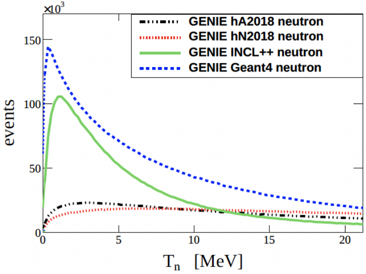
Solid **quasi-classical treatment**: It is **almost parameter free**, and it is able to successfully describe at the same time a large set of various observables [22].

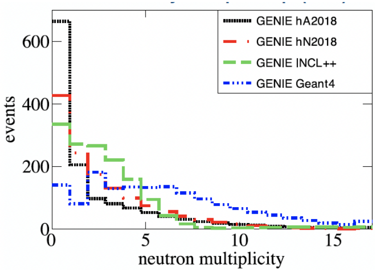
- Includes a realistic target density distribution
- The fate of all particles is followed as time evolves
- Incorporates a self-consistent determination of the stopping time
- Pauli blocking is implemented consistently with the progressive depletion of the Fermi sphere

Coupled with the ABLA [11, 37, 43] evaporation / fission code, which de-excites the remnant nucleus.

Comparisons of the 4 FSI models in GENIE

- **New models have some substantial advantages**.
- Comparisons of the FSI models accessible via GENIE highlights **modelling uncertainties**.





2 GeV

$$\nu_\mu +^{40} Ar$$

We aim to publish a paper where we **fully characterize the 4 FSI models** using our hadronic scattering data base, and then to develop a **common uncertainty model** for all 4 codes and **derive tunes** against the same datasets. Stay tuned!

Medium Energy Generator configurations - I

- **Multiple physics configurations available**
  - Main ones listed in this and the next page
  - Some minor perturbations to these also available
- **Each configuration can have multiple tunes**
- All configurations/tunes **running out of the box**

Modelling / CMC	Ground state	Cross-section: quasi-elastic	2p2h	resonance	shallow and deep inelastic	coherent π	diffractive π	$\Delta S=1$ quasi-elastic	$\Delta S=1$ inelastic	Hadronization	FSI
G00_00a G00_00b	RFG w/ NN tail	LS w/ dipole $F_A(Q^2)$	 Dytman	RS	BY	RS				AGKY AG	hA
G18_01a G18_01b G18_01c G18_01d	RFG w/ NN tail	LS w/ dipole $F_A(Q^2)$	Dytman	RS tuned (2020)	BY tuned (2020)	RS	Rein	Pais	ASAV (opt.) (ν only)	AGKY tuned (2020) AG	hA18 hN18 INCL G4B
G18_02a G18_02b G18_02c G18_02d	RFG w/ NN tail	LS w/ dipole $F_A(Q^2)$	Dytman	BS tuned (2020)	BY tuned (2020)	BS	Rein	Pais	ASAV (opt.) (ν only)	AGKY tuned (2020) AG	hA18 hN18 INCL G4B

Acronyms: **RFG**: Relativistic Fermi Gas; **LFG**: Local Fermi Gas; **LS**: Llewellyn-Smith (quasi-elastic model); **RS**: Rein and Sehgal (resonance neutrino-production, and coherent pion production models); **BY**: Bodek and Yang; **ASAV**: M. Rafi Alam, I. Ruiz Simo, M. Sajjad Athar and M.J. Vicente Vacas (single-Kaon production model); **NAV**: J.Nieves, J. Enrique Amaro, and M. Valverde (quasi-elastic model); **NSV**: J.Nieves, I. Ruiz Simo, and M.J. Vicente Vacas (2p2h model); **AGKY**: C.Andreopoulos, H.Gallagher, P.Kehayias and T.Yang (neutrino-induced hadronization model); **AG**: C.Andreopoulos, and H.Gallagher (charm hadronization model); **hA**: Effective intranuclear transport model in INTRANUKE; **hN**: Full intranuclear cascade (INC) model in INTRANUKE; **INCL**: The Liege INC model; **G4B**: Geant4 implementation of the Bertini INC model

Medium Energy Generator configurations - II

(table continued)

Modelling CMC	Ground state	Cross-section: quasi-elastic	Cross-section: 2p2h	Cross-section: resonance	Cross-section: shallow and deep inelastic	Cross-section: coherent π	Cross-section: diffractive π	Cross-section: $\Delta S=1$ quasi-elastic	Cross-section: $\Delta S=1$ inelastic	Hadronization	FSI
G18_10a	LFG	NAV w/ dipole $F_A(Q^2)$	NSV	BS tuned (2020)	BY tuned (2020)	BS	Rein	Pais	ASAV (opt.) (ν only)	AGKY tuned (2020) AG	hA18
G18_10b											hN18
G18_10c											INCL
G18_10d											G4B
G18_10i	LFG	NAV w/ $F_A(Q^2)$ from z-exp	NSV	BS tuned (2020)	BY tuned (2020)	BS	Rein	Pais	ASAV (opt.) (ν only)	AGKY tuned (2020) AG	hA18
G18_10j											hN18
G18_10k											INCL
G18_10l											G4B
G21_11a	LFG	SuSAv2 w/ dipole $F_A(Q^2)$	SuSAv2	BS tuned (2020)	BY tuned (2020)	BS	Rein	Pais	ASAV (opt.) (ν only)	AGKY tuned (2020) AG	hA18
G21_11b											hN18
G21_11c											INCL
G21_11d											G4B

- Recent model development enables an enormous variety of comprehensive configurations.
- Combinatorial explosion!

- In preparation for v4, we will construct and then tune, publish and support only a small number (<10) of configurations, based on strict criteria of physics motivation and performance against data.

High energy neutrino interactions

Complete theoretical description of high energy neutrino scattering and new tunes suitable for neutrino telescopes and the CERN FPF [38].

Several scattering mechanisms:

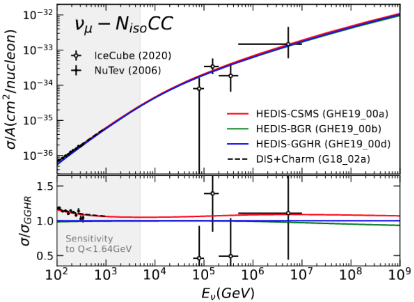
- **DIS off nucleons at NLO level**, incorporating **sub-leading resonant effects** due to neutrino interactions with the photon field of the nucleon.
- **Coherent scattering off nuclei**.
- Resonant scattering upon atomic electrons (Glashow scattering).

Structure functions are computed using the *APFEL* program [16].

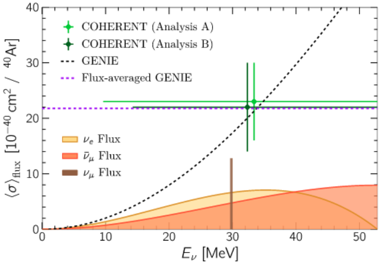
- Small-x resummation through interface to *HELL* [20].

Include 3 calculations at NLO accuracy:

- **BGR18** [17] (GHE19_00a),
- **CMS11** [28] (GHE19_00b), and
- **GGHR20** [38] (GHE19_00d).



Low-energy neutrino interactions ($\geq$ v3.2.0)



Comparison of recent CERvNS measurements from COHERENT [6] with GENIE predictions based on the model of Patton et al. [50].

- New versions of GENIE include a new CEvNS event generator
- The corresponding CEvNS cross-section calculation is based on the work of Patton et al. [50].
- The new CEvNS generator is intentionally omitted from the standard ME/HE comprehensive model configurations
- A new, dedicated LE configuration (**GVLE18_01a**) was setup, including
  - CEvNS
  - νe^-
  - IBD
- Single, baseline tune (**000_00**)

BSM models in GENIE - An overview

Substantial effort to implement & deploy **GENIE BSM generators**.

GENIE now also a lead provider of BSM simulations for intensity frontier experiments.

Available in GENIE:

- **Nucleon Decay**
- $n - \bar{n}$ **Oscillations**
- **Boosted Dark Matter** (upgraded in v3.2.0)
- **Dark Neutrinos** (new in v3.2.0)
- **Heavy Neutral Leptons** (new in v3.4.0) [51]

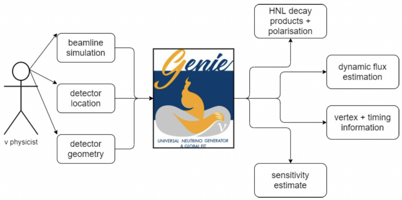
- BSM searches form an important science pillar of many neutrino experiments.
- Standard neutrino interactions are a background to BSM searches.
- **Important to simulate BSM and neutrino interactions in a common framework** (for example, using common nuclear and intranuclear hadron transport models).

Heavy Neutral Lepton generator ($\geq$ v3.4.0)

NLs are heavy neutrino eigenstates that could be produced in decays of hadrons in neutrino beams (long lifetimes $c\tau \sim$ O(100 m))

GENIE implementation by John-Komninos Plows and Xianguo Lu [51]

- Implementing effective field theory by P. Coloma et al. [26] (caveat: below kaon mass threshold)
- Detailed treatment of massive neutrino kinematics
- Simplified "2-to-2" treatment of angular momentum effects following J.-M. Levy [48]



- Generic runtime control of HNL physics parameters via single xml config-file
- Interfaced with dk2nu-like flux tuples + ROOT geometry
- Accurate vertex positioning + arrival-time calculations

Genie

GENIE global analysis

Since ∼2017, developing a **analyses of relevant scattering data**.

Essential task, as empirical approaches often augment incomplete theory.

- Goals: **Parameter estimation**, **addressing double counting** issues inherent in empirical model construction, improve extrapolations in kinematic regions of limited model validity, model **uncertainty quantification**.

Tremendous analysis infrastructure:

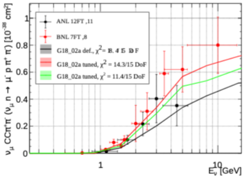
- Extensive **curated data archives** (neutrino, electron, hadron)
- Associated data/MC comparison tools, emulating experimental conditions, cuts
- **Computationally-efficient brute force scans**, adapting tools from the LHC
  - **Beyond reweighting constraints**!
- Tools enabling **massive parallelization**.

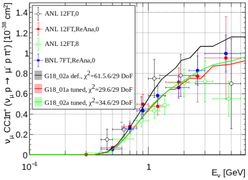
Recent published GENIE analyses:

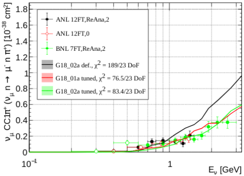
- Non-resonance bkg tuning, PRD 104 (2021) 7, 072009
- Hadronization model tuning (focus on hadron multiplicities), PRD 105 (2022) 1, 012009
- Neutrino-nucleus CC0π tuning, PRD 106 (2022) 11, 112001

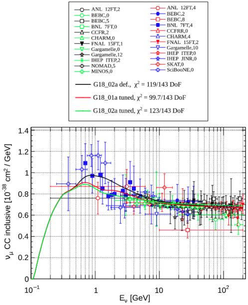
Novel new analyses in advanced stage - Goal: a **joint, global analysis**

GENIE non-resonance background tune







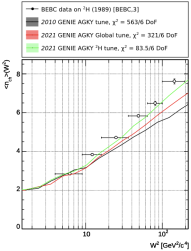


- Fit to CC inclusive, CCQE, CC1π and CC2π data for H/D.
- Adjust non-resonance parameters, while also floating QE, resonance and DIS parameters.
- **Improved description of both inclusive and exclusive data**.
- Significant changes wrt the historical tune in v2.
- **Final tuning results included in v3.2.0** and published in [58] (note: preliminary results included in earlier versions differ!)

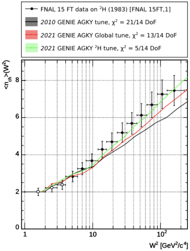
Genie

GENIE hadronization multiplicity tune

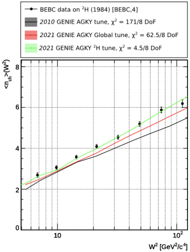
- **First tune** [57] of the **AGKY** [64] **neutrino-induced hadronization model**.
- Uses average multiplicity data on H and D.
- Tunes 13 non-reweightable parameters (see [57] or in the backup slides).
- Benchmark application, highlighting the capabilities of the GENIE global analysis.
- Improves high-W region and provides quantitative estimates of model parameter uncertainties.
- Many additional pieces of available data (see [64]). Plan to revisit and extend the tune in the near future.



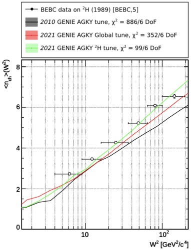
(a) $\nu_\mu + p \to \mu^- X^{++}$



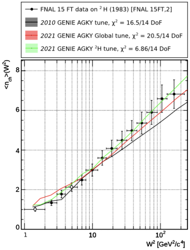
(b) $\nu_\mu + p \to \mu^- X^{++}$



(c) $\nu_\mu + n \to \mu^- X^{+}$



(d) $\nu_\mu + n \to \mu^- X^{+}$

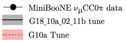


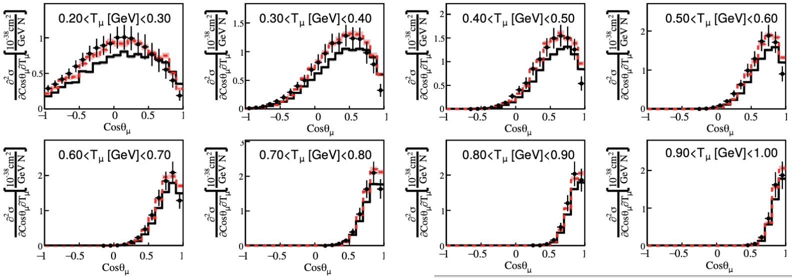
(e) $\nu_\mu + n \to \mu^- X^{+}$

Genie

GENIE nuclear CC0π tune

- First nuclear cross-section tune in GENIE, published in [56]
- Considered QE, 2p2h, resonance and FSI parameters.
- Partial tunes to T2K, MINERvA, MB data - Examined tensions.





- Didn't publish results of combined fit because of observed tensions
- We now attempt to combine data from different experiments, as well as from both 0π and 1π topologies, with a narrow focus on TKI observables.

Parameters	G10a Tune	G11a Tune	G20a Tune	G30a Tune	G31a Tune	G35a Tune
$M_A^{\mathrm{QEL}}(\mathrm{GeV/c^2})$	1.02 ± 0.01	1.01 ± 0.01	1.00 ± 0.01	1.00 ± 0.02	1.00 ± 0.01	0.99 ± 0.01
ω_{RPA}	1.20 ± 0.03	1.14 ± 0.06	1.2 ± 0.2	0.9 ± 0.1	1.3 ± 0.2	0.75 ± 0.3
$\omega_{\mathrm{No\,RPA}}$	0.05 ± 0.02	0.09 ± 0.05	-0.1 ± 0.1	0.2 ± 0.1	0.2 ± 0.2	0.09 ± 0.3
S_{RES}	0.85 ± 0.02	0.86 ± 0.05	0.84 ± 0.02	0.84 ± 0.03	0.84 ± 0.02	0.84 ± 0.02
S_N^{2p2h}	1.5 ± 0.4	2.3 ± 0.01	1.7 ± 0.3	1.2 ± 0.4	1.7 ± 0.5	0.33 ± 0.2
S_Δ^{2p2h}	0.7 ± 0.2	0.7 ± 0.3	(1.00)	2.1 ± 0.2	2.3 ± 0.2	0.5 ± 0.4
S_{PL}^{2p2h}	0.4 ± 0.1	0.4 ± 0.1	(1.00)	0.9 ± 0.2	0.4 ± 0.1	1.5 ± 0.4
χ^2	89/130	77/71	60/55	61/137	67/53	17/19

Beyond reweightability constraints

- We provided first reweight tools ~15 yrs ago.
  - **Popular paradigm** adopted by many experiments and other neutrino generators.
  - Built deeply into experiment analysis chains.
- Traditional **reweight has severe limitations**.
  - **Key modelling aspect are not reweightable** (e.g in nuclear modelling or in hadronic simulations).
- Our tuning tools **transcend these limitations**
- **GENIE leads the way quantifying uncertainty**, testing the impact of new degrees of freedom.
  - Example: Our recent hadronization tuning paper [57] **tuning 13 parameters w/o a reweighting equivalent.**
- **Experiments lack the infrastructure** to fully exploit our tunes and uncertainty estimates.
- We're working to **fully support our tunes within our reweight tools**.
  - Traditional "reweight-like" interface.
  - Systematic response functions generated in our tuning campaigns hidden under the hood.
- **Pre-requisite for GENIE v4**. Active work by a strong team (JUNO/SBND contributions).

Summary

- **Substantial developments since the release of v3 in Oct 2018**
- **GENIE v4 on the horizon**
  - Req'd devel: DCC [53, 54], MAID [59], reweighting support for tunes.
  - Will feature a novel but reduced/targeted set of ME physics configurations
  - New tuning campaign and uncertainty evaluation for preferred configurations, including new analyses (TKI and FSI global fits)

Would like to thank all our users and the dozens of contributors, working with the core team. Your contributions are essential!

To find out more:

- Join our GENIE Slack channel (by invitation, or with a FNAL or CERN e-mail)
- Follow interactions (issues, pull requests, discussions) in our GitHub page
- Join our monthly User Forum
- See our recent papers in [7, 56–58]

Supplementary Slides

High-energy neutrino interactions ($\geq$ v3.2.0) - I

Complete theoretical description of HE neutrino scattering and new tunes suitable for neutrino telescopes and the CERN FPF [38].
Distinct comprehensive models, used for energies above 100 GeV.

- Planning to bridge with ME model in future.

Validated for neutrino energies up to 10^9 GeV!

Can be coupled with tools, such as *NuPropEarth* [38] or *gSeaGen* [4].

Includes several relevant scattering mechanisms:

- **DIS off nucleons at NLO level**
  - Incorporating **sub-leading resonant DIS effects** (due to neutrino interactions with the photon field of the nucleon)
- **Coherent scattering off nuclei**
- Resonant scattering upon atomic electrons (Glashow scattering)

High-energy neutrino interactions ($\geq$ v3.2.0) - II

For DIS scattering off gluons and quarks, in the perturbative regime, the structure functions $F_i^{\nu N}$ factorise in terms of process-dependent coefficients $C_{i,a}^{\nu}$ and process-independent PDFs f_a^N as follows

$$F_i^{\nu N}(x, Q^2) = \sum_{a=g,q} \int_x^1 \frac{dz}{z} C_{i,a}^{\nu}(\frac{x}{z}, Q^2) f_a^N(z, Q^2)$$

- The coefficients $C_{i,a}^{\nu}$ can be computed in perturbation theory as a power expansion in the strong coupling constant a_s.
- The DGLAP equations determine the evolution of PDFs.
- Option to account for the impact of small-x resummation (logarithmic enhancements arising from high-energy gluon emissions) of coefficient functions and PDF evolution.

High-energy neutrino interactions ($\geq$ v3.2.0) - III

Structure functions are computed using the *APFEL* program [16].

- Small-x resummation through interface to *HELL* [20].

The baseline calculation is **BGR18** [17].

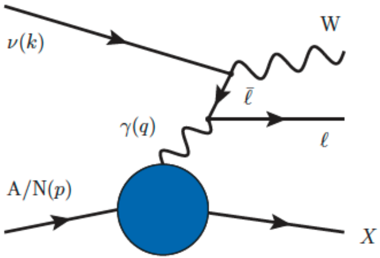
- All inputs at NLO accuracy.
- PDF sets from NNPDF3.1sx [8] global analysis of collider data.
- Incorporating (through PDF reweighting) the impact of LHCb D-meson production in pp collisions (small-x PDF constraints beyond the kinematic range of HERA data) [1–3].
- Using the FONLL scheme [36] to account for quark mass effects.
- Nuclear corrections computed using the EPPS16 nPDFs [33, 35].

The **CMS11** [28] calculation is implemented for reference.

- Uses the the NLO HERA1.5 PDF set [27].

The **GGHR20** [38] calculation is also implemented for reference.

High-energy neutrino interactions ($\geq$ v3.2.0) - IV



Resonant interactions with the nucleon's photon field, can amount to up to a 3% correction of the total DIS cross-section, when the neutrino has enough energy to produce an on-shell W boson ($\sqrt{2M_N E_\nu} \geq M_W$).

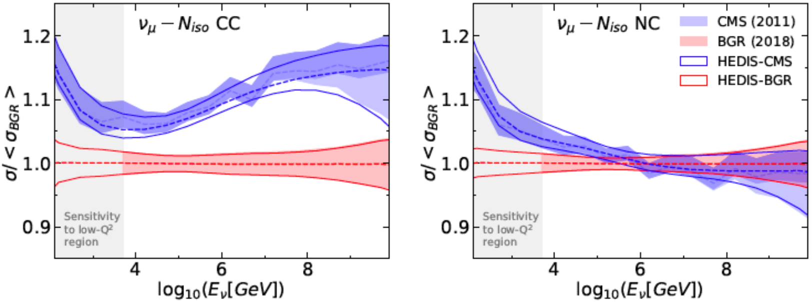
The contribution to the cross-section taken into account [38] by convoluting the cross-section for the partonic process $\nu\gamma \to \ell W$, with the inelastic photon PDF of the nucleon

$$\sigma_{\nu N}(E_\nu) = \int dx \; \gamma^N_{inel}(x, \mu_F^2) \; \hat{\sigma}_{\nu\gamma}(x, \mu_F^2, E_\nu)$$

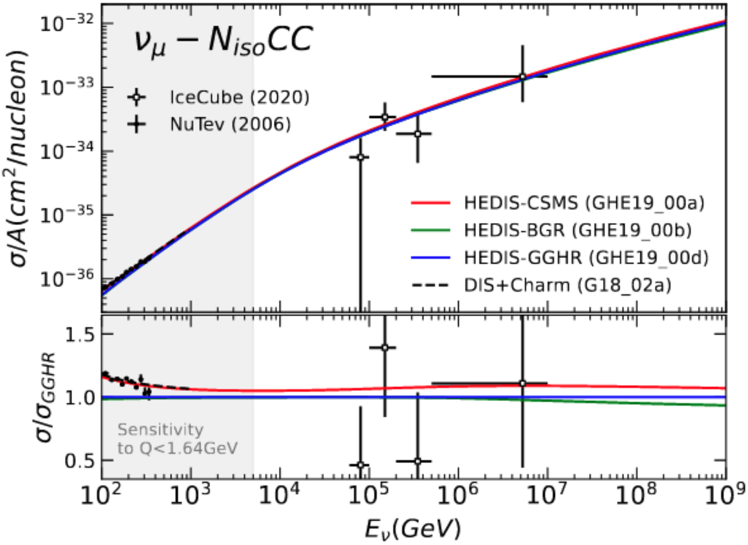
High-energy neutrino interactions ($\geq$ v3.2.0) - V

Comparison [38] of neutrino-nucleon interaction cross-sections:

- The original (NLO) BGR18 and CMS11 calculations are compared with their corresponding GENIE implementations
- Bands correspond to the PDF uncertainties



High-energy neutrino interactions ($\geq$ v3.2.0) - VI



CEvNS and VLE tunes ($\geq$ v3.2.0) - I

- **Added a new CEvNS event generator**.
- The corresponding CEvNS cross-section calculation is based on the work of Patton et al. [50].
- In this model the differential CEvNS cross-section is given by

$$\frac{d\sigma}{dT} = \frac{G_F^2}{2\pi} M \left\{ 2 - \frac{2T}{E} + \left(\frac{T}{E}\right)^2 - \frac{MT}{E^2} \right\} \frac{Q_w^2}{4} F^2(Q^2)$$

where M is the nuclear mass, T is the kinetic energy of the nuclear recoil,

$$T = \frac{Q^2 E}{2EM + Q^2},$$

CEvNS and VLE tunes ($\geq$ v3.2.0) - II

Q_w is the weak charge,

$$Q_w = N - Z(1 - 4sin^2\theta_w),$$

and $F(Q^2)$ is the nuclear form factor

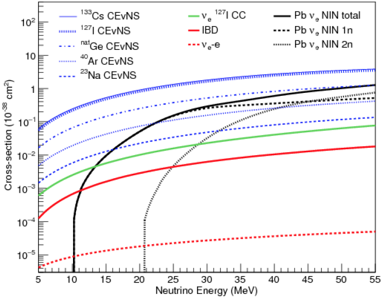
$$F(Q^2) = \frac{1}{Q_w}\int \Big(\rho_n(r) - (1 - 4sin^2\theta_w)\rho_p(r)\Big)\frac{sin(Qr)}{Qr}r^2 dr \Rightarrow$$

$$F(Q^2) = \frac{N}{Q_w}\Big(1 - \frac{Q^2}{3!} < R_n^2 > + \frac{Q^5}{5!} < R_n^4 > - \frac{Q^6}{7!} < R_n^6 > + ...\Big)$$

where

$$< R_n^k > = \frac{\int \rho_n(r) r^k d^3 r}{\int \rho_n(r) d^3 r}$$

CEvNS and VLE tunes ($\geq$ v3.2.0) - III



Calculation by Patton et al. [50] fully reproduced by GENIE implementation.

- The new CEvNS generator is omitted from the standard comprehensive model configurations
  - Large cross-section to nearly invisible channel
- A new, dedicated low-energy configuration (**GVLE18_01a**) was setup, including
  - CEvNS
  - νe^-
  - IBD
- Single, baseline tune (**000_00**)

Genie

Updated BDM generator ($\geq$ v3.2.0) - I

A native implementation of a **Boosted Dark Matter** (BDM) generator was available in GENIE 3.0.0.

A substantial upgrade of the GENIE BDM generator was deployed in GENIE 3.2.0, bringing it sync with the model described in [12]. The GENIE implementation was prepared by the original author (Josh Berger).

The newly deployed BDM code:

- allows a broader set of particle physics models, including both vector and axial couplings, as well as different isospin structures,
- as improved modeling of the elastic scattering process, including a pseudoscalar form factor,
- includes the simulation of scattering off electrons, and
- includes anti-dark matter scattering.

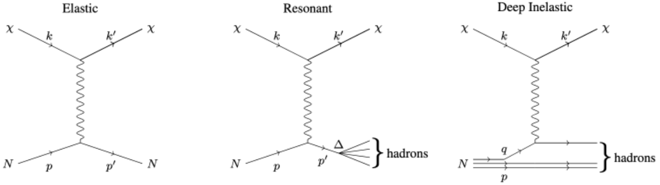
Updated BDM generator ($\geq$ v3.2.0) - II

The GENIE BDM generator covers a broad class of models:

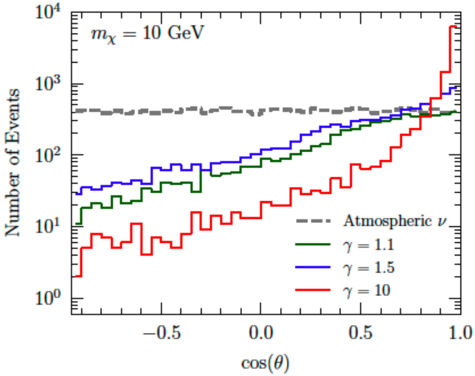
$$J^{\mu}_{Z',\psi} = \bar{\psi}\gamma^{\mu}(Q^{\psi}_{L}P_L + Q^{\psi}_{R}P_R)\psi$$

$$\mathcal{L}_{int} = g_{Z'} Z'_{\mu} J^{\mu}_{Z',\psi}$$

where $\psi = \chi, u, d, s, c, e$. The model is specified by charges Q^{ψ}_{LR}, the gauge coupling $g_{Z'}$ and the masses of the dark matter particle χ and of the mediator Z'.



Updated BDM generator ($\geq$ v3.2.0) - III



Example DUNE sensitivity study [13] using the GENIE BDM module.

Angular distribution of hadronic BDM signal wrt the direction of the Sun.
The plot shows 10k event distributions for a DM particle with a mass of 10 GeV, for 3 different boost factors γ.

Dark Neutrino generator ($\geq$ v3.2.0) - I

- Framework that provides an explanation to the long-standing excess of electronlike events in the MiniBooNE experiment at Fermilab [18]
- The model extends the SM Lagrangian including
  - A new massive "dark" neutrino that mixes with SM one

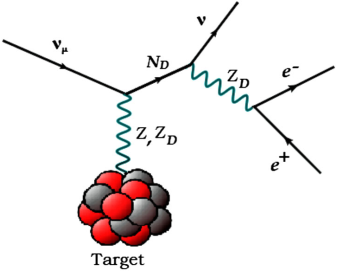
$$\nu_\alpha = \sum_{i=1}^{3} U_{\alpha i}\nu_i + U_{\alpha 4}N_4 \qquad \alpha = e, \mu, \tau, \mathcal{D} \tag{1}$$

  - light dark neutral vector boson that couples with $\nu_\mathcal{D}$ and EM charge

$$\mathcal{L}_\mathcal{D} \supset g_\mathcal{D} Z^\mu_\mathcal{D} \bar{\nu}_\mathcal{D}\gamma_\mu\nu_\mathcal{D} + e\varepsilon Z^\mu_\mathcal{D} J^{em}_\mu \tag{2}$$

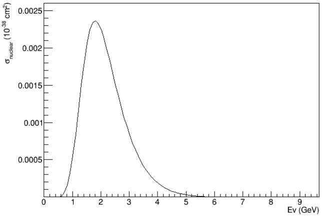
Dark Neutrino generator ($\geq$ v3.2.0) - II

- Once the heavy neutrino is produced it decays into
  - light neutrinos
  - e pair
  - μ pair - if the mass is high enough
- Decay length and branching ratios are strongly dependent on the mixing parameters and masses
  - with the parameters from [18] it can be of the order of mm or cm
  - and mostly decay into e-pair
- The new flavour can have the equivalent of any NC interaction available in the SM

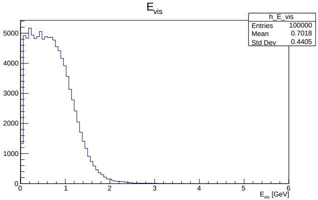


Dark Neutrino generator ($\geq$ v3.2.0) - III

- The main contribution is from Coherent interaction
  - now implemented inside GENIE
  - further interactions will be implemented later
- Implementation based on the Engel form factors [34]
  - Later more sophisticated FF can be included
- The generator also takes care of the decay of the dark particles
  - Downstream code will not need upgrades



Plots from ν_μ on ^{40}Ar

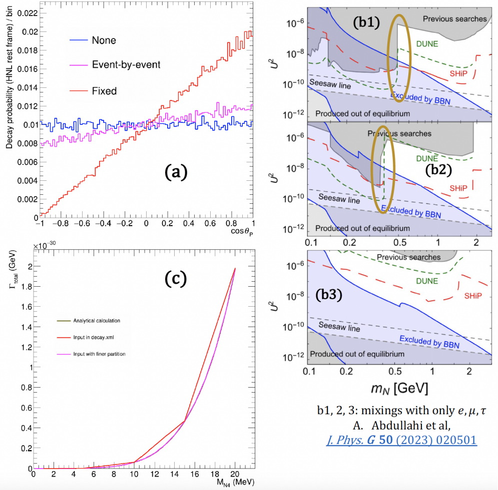


Visible energy for BNB-like beam

Heavy Neutral Lepton generator upgrades

Possible to extend the functionality in a number of ways:

- More detailed treatment of polarisation incorporates state-of-the-art QM calculations with detailed HNL kinematics (a)
- Implementation of heavier HNL production and decay channels enables searches beyond kaon mass (b1, b2) and expands searches with τ-mixing (b3).
- Extension of Lagrangian model machinery to incorporate user input (c); a comprehensive model selection for HNL generation.



b1, 2, 3: mixings with only e, μ, τ
A. Abdullahi et al,
J. Phys. G **50** (2023) 020501

Upgraded hadron tensor tools ($\geq$ v3.2.0) - I

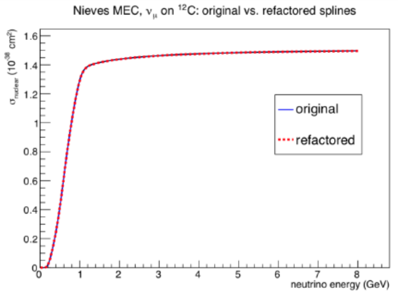
GENIE continued work to develop **suitable new code interfaces to simplify inclusion of new theoretical calculations**.

Several ideas, through comparative study of the requirements for implementing different types of 0-pion models:

- Valencia
- SuSA
- Short-time approximation
- CBF spectral function

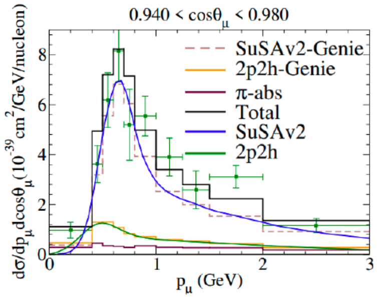
A refactoring and generalisation of code to handle hadron tensors was a necessary ingredient towards improving 0-pion theory interfaces.

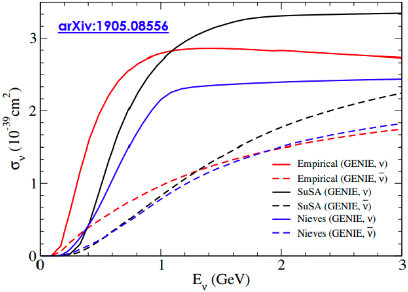
- Tech details in **GENIE docdb #137**.
- Old models migrated to new scheme.
- Physics unchanged.



New QE/MEC models: SuSAv2 ($\geq$ v3.2.0)

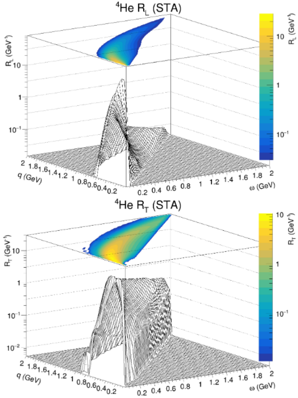
New hadron tensor tool allowed quick implementation of the SuSAv2 model. Details are given in [32].

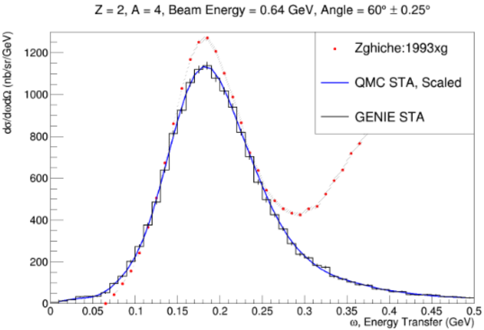




New QE/MEC models: QMC STA (> v3.2.0)

Similar tools underpin the GENIE implementation of the **Quantum Monte Carlo Short-Time Approximation** model. Details in [10].

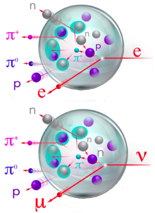


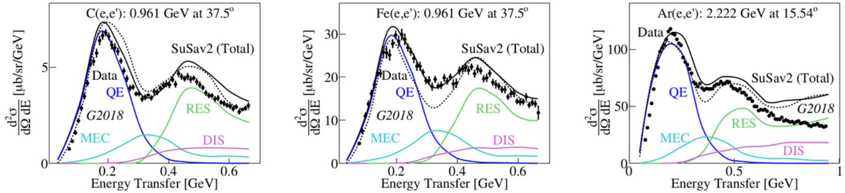


Electron scattering improvements ($\geq$ v3.0.0) - I

Renewed focus on GENIE electron mode. Details in [49]. Benchmarking of ν mode:

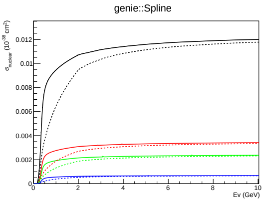
- Very similar interactions
- Nuclear effects practically identical
- Known electron beam energy





Coherent single-γ production ($\geq$ v3.2.2)

- NC photon emission reactions with heavy nuclei [61]
- At intermediate energies, dominated by the weak excitation of the $\Delta(1232)$ resonance and its subsequent decay into Nγ
  - Contributions from other resonances:
    - The effect is $< 10\%$
    - to be released in a later version
- The model takes into account
  - Pauli blocking
  - Fermi motion
  - in-medium Δ resonance broadening
- DeVries form factors for proton charge distributions [31]
- Model reliable only for $E_\gamma < 2\,\mathrm{GeV}$ and for nuclei heavier than Carbon



Integrated cross sections for ν (continuous lines) and $\bar{\nu}$ (dotted lines) on different nuclei:

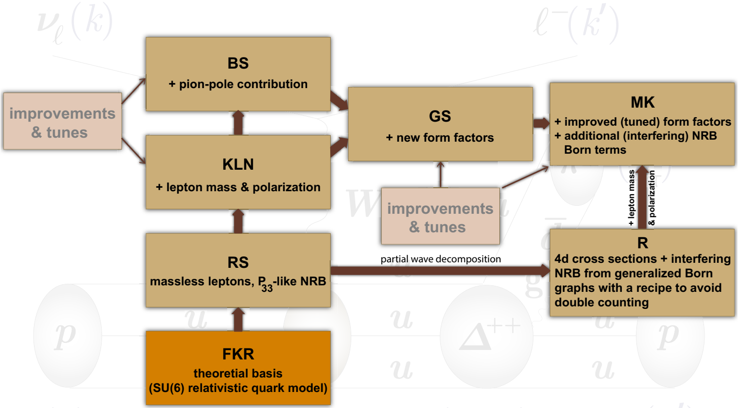
$^{12}\mathrm{C}$ - blue
$^{40}\mathrm{Ar}$ - green
$^{56}\mathrm{Fe}$ - red
$^{208}\mathrm{Pb}$ - black

New 1π models: MK ($\geq$ v3.6.0) - I

Complete implementation of the MK model by the Dubna group.

- The model calculates $\dfrac{d\sigma}{dW\,dQ^2 d\cos\theta_\pi d\varphi_\pi}$ for CC and NC processes.
- Takes into account:
  - the interference between resonances,
  - non-resonant background (calculated according to [42]),
  - the interference between resonant and non-resonant background.
  - final lepton mass.
- For theoretical aspects, see Refs. [44, 45].
- Can be analytically integrated over φ_π which allows faster numerical integration.
- The model parameters such as resonance masses, widths, branching ratios and decay channels were updated according to PDG-2018 [55].

New 1π models: MK ($\geq$ v3.6.0) - II



The genealogical tree of MK model (Igor Kakorin, Konstantin Kuzmin, Vadim Naumov)

Resonance pion decay updates ($\geq$ v3.0.6) - I

- Baryon resonance decay is not isotropic in Δ reference frame
  - The pion follows a distribution as function of θ^*
- The previous version was bugged
  - The angles were calculated with respect to the LAB z direction
  - It should be w.r.t. $\vec{q}$
- We took the opportunity and we made refinements
  - Different angular distribution options informed by data
    - ANL [52]
    - early BNL [9]
    - late BNL [46, Figure 13]
  - Distributions depend on Q^2
  - Possible dependencies on ϕ^*

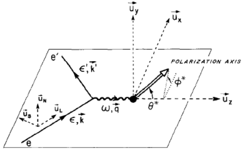
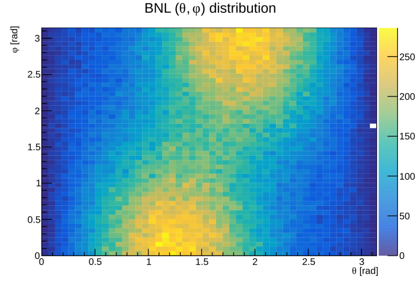


FIG. 2. Kinematics and coordinate systems for the scattering of polarized electrons from polarized nuclear targets.

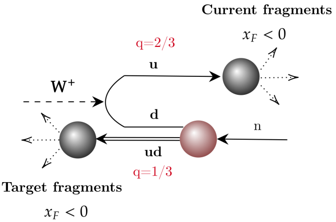


Hadronization

Hadronization models are a key ingredient for predictions of **exclusive hadronic multiparticle production**.

It affects:

- E_ν reconstruction (detector response to hadronic showers)
- Efficiency / background estimation



νn neutrino interaction.

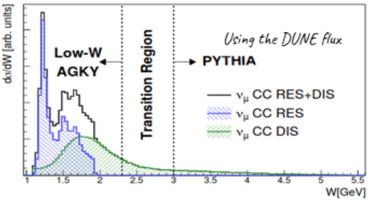
Conventional picture:

- Two correlated hadron jets (current and target fragments)
- Smooth transition through a central rapidity region
- At low W, the two fragmentation regions overlap

Hadronization model development in GENIE

GENIE AGKY Hadronization model [64]
Further details in this NuSTEC talk

- Empirical model at W $<$ 2.3 GeV
- PYTHIA at W $>$ 3 GeV
  - `home.thep.lu.se/Pythia/`
- Linear transition in between

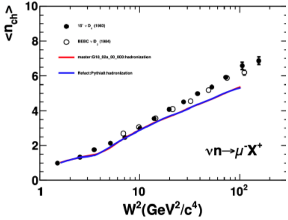


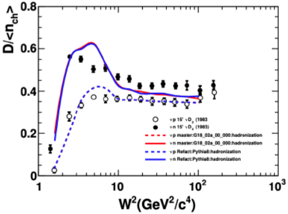
Hadronization is one of the current focal areas of development:

- **Integrate PYTHIA8**
- Improve GENIE/PYTHIA interface (gluon radiation)
- In-medium effects
- Relax strong x_F asymmetry at low W
- Non asymptotic forms of KNO scaling
- Address double-counting following introduction of $\Delta S{=}1$ modes
- **Parameter tuning**
- **Evaluation of model uncertainty**
- Tools for propagating hadronization model uncertainty
- ...

Interface to PYTHIA8 ($\geq$ v3.2.0) I

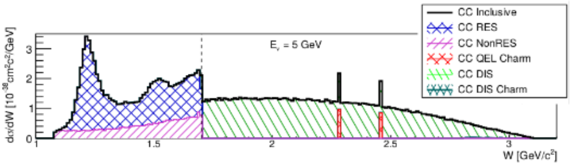
- Large-scale code refactoring completed.
- Changed of hadronization and decayer interfaces
  - Upgrade to *event record visitors*
  - Eliminated PYTHIA6-specific (but misunderstood as generic) ROOT objects (TMCParticle) from interfaces
- Interfaced to PYTHIA8 directly (not via ROOT)
- **PYTHIA8 is a working PYTHIA6 alternative within AGKY**
  - PYTHIA6/8 yield identical results
- **PYTHIA8 not a full PYTHIA6 replacement yet**
  - Particle decayers, charm hadronization, LEPTO (HEDIS) still support only PYTHIA6
  - Fully transition to PYTHIA8 in v3.4
  - Drop PYTHIA6 entirely in v4.0
- Still useful for exercising / testing new future mandatory dependency.





Transition region tuning ($\geq$ v3.2.0) - I

- Resonance production is described with the Rein-Sehgal or Bergher-Seghal models
- Non-resonant bkg. is described using the duality inspired model of Bodek-Yang
  - Bodek-Yang cross section extrapolated down to the inelastic threshold
  - GENIE low-mass hadronization model is used to decompose the inclusive cross section into exclusive cross sections
  - Strength includes, on average, the effect of the resonances



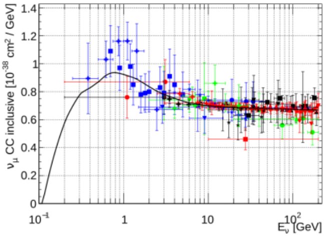
Tuning is needed to address double-counting with resonances

Using ν_μ / $\bar{\nu}_\mu$ CC data ($\sim$ 200 points) on H, H^2 targets for the following topologies:

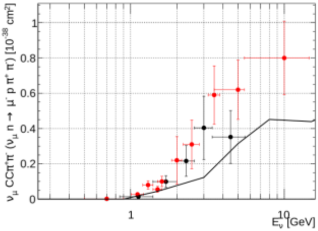
- Inclusive
- 1π production ($\nu_\mu n \to \mu^- n\pi^+$, $\nu_\mu p \to \mu^- p\pi^+$, $\nu_\mu n \to \mu^- p\pi^0$, $\bar{\nu}_\mu p \to \mu^+ p\pi^-$)
- 2π production ($\nu_\mu p \to \mu^- n\pi^+\pi^+$, $\nu_\mu p \to \mu^- p\pi^+\pi^0$, $\nu_\mu n \to \mu^- p\pi^+\pi^-$)
- Quasi-elastic (to constrain flux normalization)

Transition region tuning ($\geq$ v3.2.0) - II

- In the old tune, **more emphasis was given on inclusive data**
- **Tensions exist between inclusive and exclusive data**
  Known issues with the old tune, re-discovered many times:
  - One pion production was overpredicted
  - Underestimating two pion production



G00_00a default - ν_μ CC inclusive



G00_00a default - ν_μ CC p$\pi^+\pi^-$

Transition region tuning ($\geq$ v3.2.0) - III

Experiment	N_p	Energy [GeV]	Target	Cuts	Ref.
		$\nu_\mu + N \to \mu^- X$			
BNL 7FT	13	0.6-10	^{2}H		[42]
BEBC	3	10-50	H-^{10}Ne		[40]
FNAL	6	10-110	^{2}H		[72]
	5	100-110	H-^{10}Ne		[45]
		$\bar{\nu}_\mu + N \to \mu^+ X$			
BEBC	3	11-110	^{1}H-^{10}Ne		[28]
	1	10-50	^{1}H-^{10}Ne		[40]
	6	30-110	^{1}H-^{10}Ne		[29]
	1	10-110	^{1}H-^{10}Ne		[41]
BNL 7FT	1	1-4	^{1}H		[51]
FNAL	5	10-110	^{2}H$-^{10}$Ne		[47]
	7	10-80	^{2}H$-^{10}$Ne		[52]
		$\nu_\mu n \to \mu^- n \pi^+$			
ANL 12FT	5	0.3-2	^{1}H and ^{2}H		[65]
ANL 12FT,ReAna	7	0.3-3	^{2}H		[66]
BNL 7FT,ReAna	11	0.1-4	^{2}H		[66]
		$\nu_\mu p \to \mu^- p \pi^+$			
ANL 12FT,ReAna	8	0-1.6	^{2}H		[66]
BNL 7FT,ReAna	7	0-7	^{2}H		[66]
BEBC	7	1-30	^{1}H	$W < 1.4$ GeV	[68]
	6	5-100	^{2}H	$W < 2$ GeV	[56]
	5	10-80	^{1}H	$W < 2$ GeV	[70]
FNAL	3	10-30	^{1}H	$W < 1.4$ GeV	[75]
		$\nu_\mu n \to \mu^- p \pi^0$			
ANL 12FT	5	0.2-2	^{1}H and ^{2}H		[65]
ANL 12FT,ReAna	7	0.2-2	^{2}H		[66]
BNL 7FT,ReAna	10	0.4-3	^{2}H		[66]
		$\nu_\mu p \to \mu^- n \pi^+ \pi^+$			
ANL 12FT	5	1-6	^{2}H		[73]
		$\nu_\mu p \to \mu^- p \pi^+ \pi^0$			
ANL 12FT	5	1-6	^{2}H		[73]
		$\nu_\mu n \to \mu^- p \pi^+ \pi^-$			
ANL 12FT	5	8-6	^{2}H		[73]
BNL 7FT	10	0-20	^{2}H		[33]
		$\bar{\nu}_\mu p \to \mu^+ p \pi^-$			
FNAL	1	5-70	^{1}H	$W < 1.9$ GeV	[71]
		$\nu_\mu + n \to \mu^- + p$			
ANL 12FT	7	0-2	^{2}H		[55]
	8	0-2	^{1}H and ^{2}H		[27]
BNL 7FT	4	0.2-2	^{2}H		[60]
BEBC	5	20-40	^{2}H		[56]
FNAL	2	0-50	^{2}H		[57]

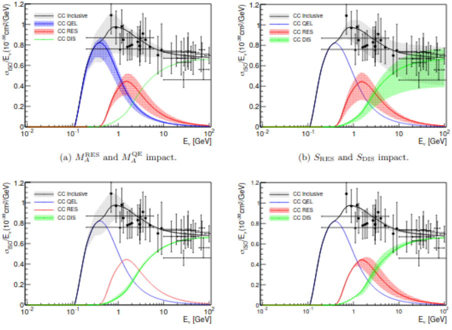
The SIS region is tuned against ν_μ / $\bar{\nu}_\mu$ CC data on ^2H targets for the following **topologies**:

- Inclusive
- One pion production
  - $\nu_\mu n \to \mu^- n \pi^+$
  - $\nu_\mu p \to \mu^- p \pi^+$
  - $\nu_\mu n \to \mu^- p \pi^0$
  - $\bar{\nu}_\mu p \to \mu^+ p \pi^-$
- Two pion production
  - $\nu_\mu p \to \mu^- n \pi^+ \pi^+$
  - $\nu_\mu p \to \mu^- p \pi^+ \pi^0$
  - $\nu_\mu n \to \mu^- p \pi^+ \pi^-$
- Quasi-elastic data†

† To constrain flux normalization

Transition region tuning ($\geq$ v3.2.0) - IV

1. RES parameters
   - M_A^{RES}
   - RES-XSecScale
2. SIS parameters
   - W_{cut} to determine the end of the SIS region
   - R_m parameters for proton and neutron, multiplicity 2 and 3
3. DIS parameters
   - DIS-XSecScale
4. QEL parameters
   - M_A^{QEL}
5. Flux nuisance parameters



(a) $M_A^{\rm RES}$ and $M_A^{\rm QE}$ impact. (b) $S_{\rm RES}$ and $S_{\rm DIS}$ impact. (c) $R_{\nu p}^{\rm CC1\pi}$, $R_{\nu p}^{\rm CC2\pi}$, $R_{\nu n}^{\rm CC1\pi}$ and $R_{\nu n}^{\rm CC2\pi}$ impact. (d) $W_{\rm cut}$ impact.

These parameters are common for both G18_01a and G18_02a CMC

Transition region tuning ($\geq$ v3.2.0) - V

- The datasets from the same experiment are not independent
  $\Rightarrow$ same flux, analysis methodology,...
- The data releases do not contain any correlation
- By adding an **extra nuisance parameters** per experiment we take into account the correlation
  $\rightarrow$ ν and $\bar{\nu}$ beams have different nuisance parameters
- They are **scaling factors** applied to the prediction
- Each nuisance parameter has a Gaussian prior centered on 1 with $\sigma = 15\%$
- To further constrain the fluxes, **we included quasi-elastic data as well as M_A^{QE} in the fit**

Transition region tuning ($\geq$ v3.2.0) - VI

Parameter	Default	G18_01a(/b)	G18_02a(/b)
W_{cut}	1.7	1.94	1.81
M_A^{QE}	0.99	1.00 ± 0.01	1.00 ± 0.013
M_A^{RES}	1.12	1.09 ± 0.02	1.09 ± 0.014
$R_{\nu p}^{\text{CC}1\pi}$	0.1	0.06 ± 0.03	0.008
$R_{\nu p}^{\text{CC}2\pi}$	1	1.1 ± 0.2	0.94 ± 0.075
$R_{\nu n}^{\text{CC}1\pi}$	0.3	0.14 ± 0.03	0.03 ± 0.010
$R_{\nu n}^{\text{CC}2\pi}$	1	2.8 ± 0.4	2.3 ± 0.12
S_{RES}	1	0.89 ± 0.04	0.84 ± 0.028
S_{DIS}	1.032	1.03 ± 0.02	1.06 ± 0.01
χ^2/157 DoF		1.84	1.64

$\Rightarrow$ The correlation between the tuned parameters is in the backup slides

Priors applied

$M_A^{QE} = 1.014 \pm 0.014$ GeV/c^2, [ArXiv:0708.1946]
$M_A^{RES} = 1.12 \pm 0.03$ GeV/c^2, [ArXiv:0606184]

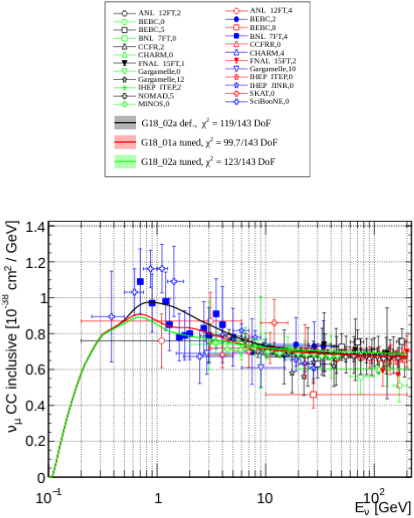
DIS-XSecScale$= 1 \pm 0.05 \rightarrow$ Motivated by DIS high energy cross section values

Genie

Transition region tuning ($\geq$ v3.2.0) - VII

Global tune with respect to ν_μ CC Inclusive datasets:

- The cross section is reduced at low energies to match the low cross section of pion production
- Pion production is better described without ruining the inclusive cross section

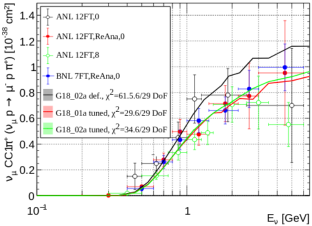


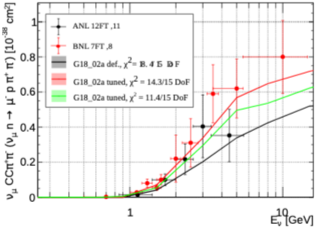
Disclaimer: Only filled data points are used in the tune

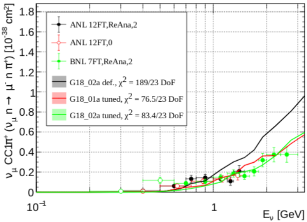
Genie

Transition region tuning ($\geq$ v3.2.0) - VIII

Retune brings an **improved description of both inclusive and exclusive data**.



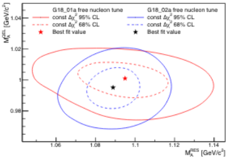




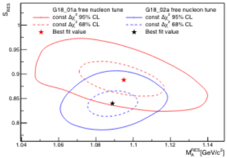
Genie

Transition region tuning ($\geq$ v3.2.0) - IX

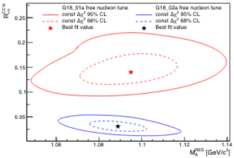
New data-driven constraints on generator uncertainty.
Our goal is that with GENIE v4, *ReWeight* will **support error propagation for all GENIE tunes** (including the intrinsically non-reweightable parameters included in tunes).



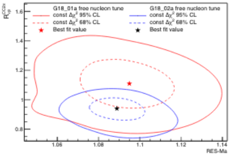
(a) Contour M_A^{RES} vs M_A^{QE}



(b) Contour M_A^{RES} vs S_{RES}



(c) Contour M_A^{RES} vs $R_{\nu n}^{\mathrm{CC}1\pi}$



(d) Contour M_A^{RES} vs $R_{\nu p}^{\mathrm{CC}2\pi}$

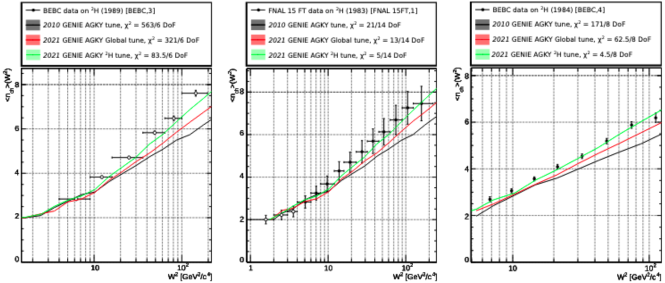
Hadronization retune ($\geq$ v3.2.0) - I

Several measurements on H and H^2 of hadronic multiplicities. See [57] for a summary.

Corresponding GENIE predictions affected by many non-reweightable parameters:

Parameter	GENIE parameter name	*2010* GENIE	Allowed range	*2021* Global Fit	*2021* ^{2}H Fit
		Low-W empirical model			
$\alpha_{\nu p}$	`KNO-Alpha-vp`	0.40	$[-1.0, 2.0]$	1.1 ± 0.3	1.2 ± 0.4
$\alpha_{\nu n}$	`KNO-Alpha-vn`	-0.20	$[-1.0, 2.0]$	$1.75^{+0.14}_{-0.11}$	-0.58 ± 0.07
$\alpha_{\bar{\nu} p}$	`KNO-Alpha-vbp`	0.02	$[-1.0, 2.0]$	$1.32^{+0.16}_{-0.14}$	1.9 ± 0.08
$\alpha_{\bar{\nu} n}$	`KNO-Alpha-vbn`	0.80	$[-1.0, 2.0]$	1.11 ± 0.09	1.07 ± 0.3
$\beta_{\nu p}$	`KNO-Beta-vp`	1.42	$[0.0, 2.5]$	0.79 ± 0.15	0.9 ± 0.3
$\beta_{\nu n}$	`KNO-Beta-vn`	1.42	$[0.0, 2.5]$	0.5 ± 0.1	1.9 ± 0.3
$\beta_{\bar{\nu} p}$	`KNO-Beta-vbp`	1.28	$[0.0, 2.5]$	0.8 ± 0.1	0.3 ± 0.1
$\beta_{\bar{\nu} n}$	`KNO-Beta-vbn`	0.95	$[0.0, 2.5]$	$0.88^{+0.09}_{-0.08}$	0.9 ± 0.2
		PYTHIA			
$P_{s\bar{s}}$	`PYTHIA-SSBarSuppression`	0.30	$[0.0, 1.0]$	0.27 ± 0.04	0.29 ± 0.05
$\langle p_\perp^2 \rangle$ [GeV^2/c^2]	`PYTHIA-GaussianPt2`	0.44	$[0.1, 0.7]$	0.46 ± 0.05	0.43 ± 0.04
E_{CutOff} [GeV]	`PYTHIA-RemainingEnergyCutoff`	0.20	$[0.0, 1.0]$	0.30 ± 0.04	0.24 ± 0.05
Lund a	`PYTHIA-Lunda`	0.30	$[0.0, 2.0]$	1.53 ± 0.13	1.85 ± 0.15
Lund b [c^4/GeV^2]	`PYTHIA-Lundb`	0.58	$[0.0, 1.5]$	1.16 ± 0.09	1.0 ± 0.2
			$\chi^2 =$	87.9/62 DoF	29.5/32 DoF

Hadronization retune ($\geq$ v3.2.0) - II

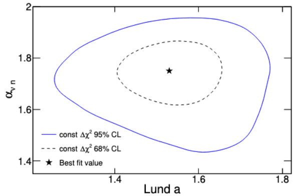


(a) $\nu_\mu + p \rightarrow \mu^- X^{++}$ (b) $\nu_\mu + p \rightarrow \mu^- X^{++}$ (c) $\nu_\mu + n \rightarrow \mu^- X^{+}$

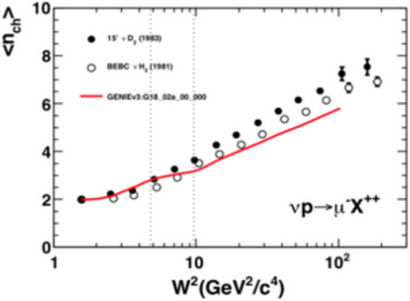
Improved description of data and first data-driven uncertainties and correlations.

For details see arXiv:2106.05884[hep-ph] (Accepted for publication in Phys.Rev.D.)

Only a first step towards more comprehensive ν-induced hadronization development and tuning work.



Hadronization retune ($\geq$ v3.2.0) - I



Decided to address:

- $\langle n_{ch} \rangle$ underestimation at the PYTHIA region
- No explicit GENIE tune
- Lack of data-driven constraints to quantify the generator uncertainty

$< n_{ch} >$ is controlled by a large set of non-reweightable parameters. Test-driving aspects of our tuning machinery, relevant for several future tunes.

Hadronization retune ($\geq$ v3.2.0) - II

In the empirical GENIE model, the averaged charged multiplicity follows an empirical logarithmic law:

$$\langle n_{ch} \rangle = \alpha_{ch} + \beta_{ch} \cdot \ln\left(\frac{W^2}{GeV^2/c^4}\right) + \cancelto{0}{\beta'_{ch}} \cdot \ln\left(\frac{Q^2}{GeV^2/c^2}\right)$$

- α_{ch} and β_{ch} are free parameters and depend on the type of interaction
- In GENIE, α_{ch} and β_{ch} are those measured by the FNAL 12FT and BEBC 7FT bubble chambers.

Parameter	νp	νn	$\bar{\nu}$p	$\bar{\nu}$n
α_{ch}	0.40	-0.20	0.02	0.80
β_{ch}	1.42	1.42	1.28	0.95

Hadronization retune ($\geq$ v3.2.0) - III

At high W, GENIE is based on the Lund string fragmentation framework (PYTHIA).

- Tuned to high energy pp and ep experiments.
- NOMAD (NUX) PYTHIA6 tuning was adopted in 2007.
- Some PYTHIA6 defaults were restored in later GENIE re-tune (2010).
- Not previously tuned with neutrino data

	PYTHIA default	NUX 2001	GENIE 2010 re-tune
$s\bar{s}$ production suppression	0.30	0.21	0.30
$< p_T^2 > (GeV^2)$	0.36	0.44	0.44
Non-gaussian p_T tail parameterization	0.01	0.01	0.01
Fragmentation cut-off energy (GeV)	0.80	0.20	0.20

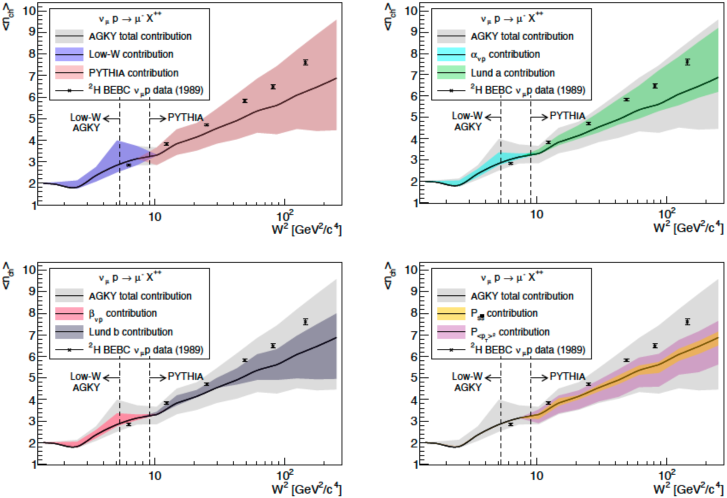
Hadronization retune ($\geq$ v3.2.0) - IV

Experiment	N_p	W^2 [GeV^2/c^4]	Cuts	Syst.	In Fit	Ref.
			$\nu_\mu + p \to \mu^- X^{++}$			
FNAL 15FT (1983)	14	[1, 225]	$p^\mu \geq 5$ GeV/c $p^T_\mu \geq 1$ GeV/c $p_L^{Ch} \geq 5$ GeV/c $p_p \leq 340$ MeV/c^2 $W \geq 1.5$ GeV/c^2 $E_\nu^{reco} \geq 10$ GeV	10%	$W^2 > 4\mathrm{GeV}^2/c^4$	[35]
BEBC (1989)	6	[4, 196]	ε_{cut} $p^\mu \geq 4$ GeV/c $p_p \leq 300$ MeV/c	included	×	[56]
			$\nu_\mu + n \to \mu^- X^+$			
FNAL 15FT (1983)	14	[1, 225]	$p^T_\mu \geq 1$ GeV/c $p_L^{Ch} \geq 5$ GeV/c $E_\nu^{reco} \geq 10$GeV $p_p \leq 340$ MeV/c^2	10%	✓	[35]
BEBC (1984)	8	[6, 112]	ε_{cut} $p^\mu \geq 4$ GeV/c $Q^2 \geq 1$ (GeV/c)^2 $W^2 \geq 5$ GeV^2/c^4 $p_p \leq 300$ MeV/c^2	~ stat	✓	[57]
BEBC (1989)	6	[4, 196]	ε_{cut} $p^\mu \geq 4$ GeV/c $p_p \leq 300$ MeV/c $W \geq 5$GeV/c^2	included	×	[56]
			$\bar{\nu}_\mu + p \to \mu^+ X^0$			
BEBC (1982)	8	[5, 75]	$p^\mu \geq 4$ GeV/c $p_p \leq 300$ MeV/c	~ stat	✓	[36]
BEBC (1989)	6	[4, 196]	ε_{cut} $p^\mu \geq 4$ GeV/c $p_p \leq 300$ MeV/c	included	×	[56]
			$\bar{\nu}_\mu + n \to \mu^+ X^-$			
BEBC (1982)	8	[1.5, 56]	$p^\mu \geq 4$ $p_p \leq 300$ MeV/c	~ stat	✓	[36]
BEBC (1989)	6	[4, 196]	ε_{cut} $p^\mu \geq 4$ $p_p \leq 300$ MeV/c	included	×	[56]

Parameter	GENIE parameter name	Nominal value	Allowed range
	Low-W empirical model		
$\alpha_{\nu p}$	KNO-Alpha-vp	0.40	[-1.0, 2.0]
$\alpha_{\nu n}$	KNO-Alpha-vn	-0.20	[-1.0, 2.0]
$\alpha_{\bar{\nu} p}$	KNO-Alpha-vbp	0.02	[-1.0, 2.0]
$\alpha_{\bar{\nu} n}$	KNO-Alpha-vbn	0.80	[-1.0, 2.0]
$\beta_{\nu p}$	KNO-Beta-vp	1.42	[0.0, 2.5]
$\beta_{\nu n}$	KNO-Beta-vn	1.42	[0.0, 2.5]
$\beta_{\bar{\nu} p}$	KNO-Beta-vbp	1.28	[0.0, 2.5]
$\beta_{\bar{\nu} n}$	KNO-Beta-vbn	0.95	[0.0, 2.5]
	PYTHIA		
$P_{s\bar{s}}$	PYTHIA-SSBarSuppression	0.30	[0.0, 1.0]
$P_{<p_T^2>}$ [GeV^2]	PYTHIA-GaussianPt2	0.44	[0.1,0.7]
$P_{E_{cut\,off}}$ [GeV]	PYTHIA-RemainingEnergyCutoff	0.20	[0.0 ,1.0]
$Lund\ a$	PYTHIA-Lunda	0.30	[0.0,2.0]
$Lund\ b$ [GeV/c^2]	PYTHIA-Lundb	0.58	[0.0,1.5]

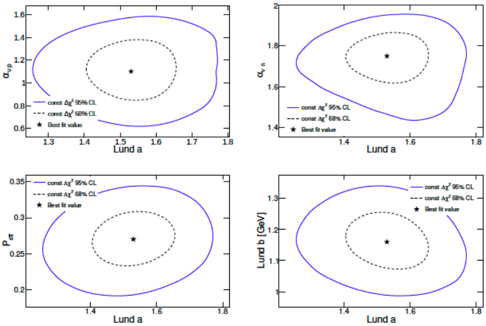
Large set of neutrino-induced hadron shower characteristic data were brought into the first hadronization tune focussing explicitly on $< n_{ch} >$. A large set of non-reweightable parameters was allowed to float.

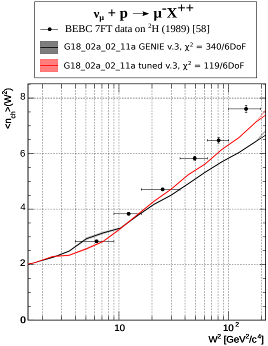
Hadronization retune ($\geq$ v3.2.0) - V

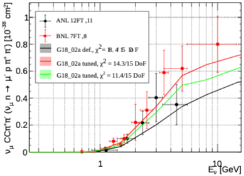


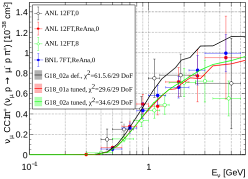
Hadronization retune ($\geq$ v3.2.0) - VI

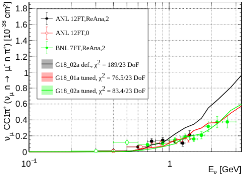
- Desired increase $\langle n_{ch} \rangle$ at the PYTHIA region
- Full error matrix for several key modelling parameters

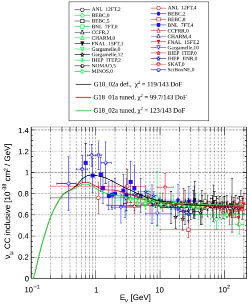












Improved description of both inclusive and exclusive data.

Final tuning results included in v3.2.0.

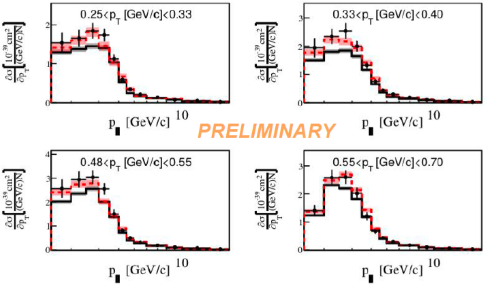
For details: arXiv:2104.09179[hep-ph] (Published in Phys.Rev.D 104 (2021) 7, 072009)

Nuclear tuning - I

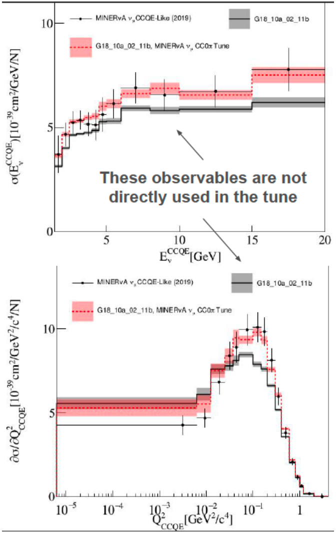
- We develop **new tunes based on nuclear cross-section data**
  - All our models to date not explicitly tuned against neutrino-nucleus data
- Based on GENIE's **G18_10a_02_11b** comprehensive model
- Our analysis includes **11 CC0π datasets** (1000 data points) from MicroBooNE, T2K ND280, MINERvA and MicroBooNE.
- Tune includes several degrees of freedom for interactions on nuclei:
  - QE: several parameters controlling the axial form factor and RPA corrections
  - MEC: several parameters affecting strength and shape in $q_0, |\vec{q}|$ space
  - RES: a scaling parameter
  - FSI: parameters controlling pion absorption and mean free path.
- Performing joint analyses and analyses of individual datasets
- We're aiming to **publish first results in March, and include the tuning results in future v3.2 revisions**.
- Longer-term goal is to perform similar analyses using all comprehensive models in GENIE.

Nuclear tuning - II

Example comparison of MINERvA data with our nominal (black) and tuned (red) model from one of our partial fits.



Details in a comprehensive new paper to be published this spring.



Event Library Generator Interface ($\geq$ v3.2.0) - I

- Ability to read from an external library of cross-sections and pre-computed final particle kinematics
  - Possibly computed using an alternative neutrino generator
- GENIE will use:
  - the appropriate cross-section from the file
  - kinematics from the library entry with the closest-matching energy

$\Rightarrow$ this will then reproduce the physics of the external generator

  - Making use of the flux and geometry handling of GENIE
  - Within the limits of the library statistics

Genie

Event Library Generator Interface ($\geq$ v3.2.0) - II

- xsec and kinetmatics to be provided for every combination of
  - Target, Interaction, ν flavour
- ROOT file input
- For each combination directory there will be
  - `TGraph` for xsection vs energy
  - `TTree` for kinematics
- `TTree` with the following branches
  - E_ν
  - `int` prod_id
  - nparts
  - array of pdgs
  - array of Final state momenta

- Structure of the input

```
H1/
        ...     ...
C12/
        cc/
                nu_mu/
                nu_mu_bar/
                nu_e/
                ...
        nc/
                nu/
                nu_bar/
O16/
        ...     ...
Cl35/
        ...     ...
```

References I

[1] R Aaij et al. "Prompt charm production in pp collisions at sqrt(s)=7 TeV". In: *Nucl. Phys. B* 871 (2013), pp. 1–20. DOI: 10.1016/j.nuclphysb.2013.02.010. arXiv: 1302.2864 [hep-ex].

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